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13. ABSTRACT (Maximum 200 words)

This work is comprised of a comprehensive investigation of the evolution and stability of, and the turbulent mixing and fluxes within, the stable nocturnal boundary layer (NBL) using the Cooperative Atmosphere-Surface Exchange Study (CASES) instrumented site in south central Kansas and the greatly enhanced in-situ instrumentation to be deployed during CASES-99. It was motivated by the need to establish the role of the NBL and phenomena within the NBL in surface and boundary layer heat and momentum fluxes. We have used the correlative high-resolution measurements of turbulence generation and mixing during CASES-99 to 1) understand the dynamics and characteristics of turbulence in the NBL, 2) identify the dominant sources of turbulence, and 3) quantify the heat and momentum fluxes, for the improvement of existing parameterization. During the 2 year period of the contract we completed extensive observational analyses and quantification of NBL flux, including data analysis from the Intensive Observational Periods (IOPs). Our research has been extensive and significantly progressed the atmospheric science field's knowledge of the processes contributing to turbulent mixing and transport in the stable NBL and has specifically enabled their more quantitative parameterization, with direct future impacts on the improved numerical simulation of severe dispersion periods.

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Surface Layer Flux Sources and Parameterization Failure in Stable Conditions from CASES-99 Data Analysis: Impacts of Intermittent Turbulence its Sources and a Proposed Solution

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1) Foreward

This work is comprised of a comprehensive investigation of the evolution and stability of, and the turbulent mixing and fluxes within, the stable nocturnal boundary layer (NBL) using the Cooperative Atmosphere-Surface Exchange Study (CASES) instrumented site in south central Kansas and the greatly enhanced in-situ instrumentation to be deployed during CASES-. It was motivated by the need to establish the role of the NBL and phenomena within the NBL in surface and boundary layer heat and momentum fluxes. It is known that a variety of atmospheric phenomena influence these fluxes, such as gravity wave propagation, shear instability, gravity currents, stratified turbulence, mesoscale motions, and strong radiative effects. Various combinations of these phenomena likely account for turbulence intensities and intermittency, and the corresponding fluxes, within the stable NBL, and therefore its complicated scalar dispersion. We have used the correlative high-resolution measurements of turbulence generation and mixing during CASES-99 to 1) understand the dynamics and characteristics of turbulence in the NBL, 2) identify the dominant sources of turbulence, and 3) quantify the heat and momentum fluxes, for the improvement of existing parameterization.

The CASES-99 field program was held in October 1999 east of Wichita, Kansas. CASES-99 instrumentation defined the meso-γ and micro-α scale boundary layer evolution and structure. Existing data sources in and around the field site provided enhanced ground-based and surface flux instrumentation. In-situ boundary-layer instrumentation defined the evolving temperature, wind, and constituent profiles and the wave, eddy, and turbulence fluxes of heat and momentum. In addition to ARO contributions, instrumentation was supplied by, 1) an NCAR facility request and 2) Argonne National Laboratory, 3) NOAA, 4) European organizations, 5) Universities, and 6) other organizations.

During the 2 year period of the contract we completed extensive observational analyses and quantification of NBL flux, including data analysis from the Intensive Observational Periods (IOPs). By correlating the measurements from relevant platforms and using those instruments that directly measure fluxes (the airborne instruments, lidar, the 60 m and other towers), we have quantified the impact of various phenomena on NBL fluxes. In the second year we focussed on dynamical causes of intermittency and the development of quantitative representation of NBL flux evolution. Our research has been extensive and significantly progressed the atmospheric science field's knowledge of the processes contributing to turbulent mixing and transport in the stable NBL and has specifically enabled their more quantitative parameterization.

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3) List of Appendices, Tables and Illustrations (*illustrations only*)

Figure 1: a) σ_H and σ_{Hp} (Louis 1981 [dots] and Delage 1997 [stars]) versus Ri_b and b) H and H_p (Louis 1981 and Delage 1997) versus Ri_b. Insufficient data does not allow the drawing of a meaningful line beyond $Ri_b = 2.0$ in b). Standard deviation ranges are also shown in b) for some of the data.

Figure 2: a) σ_{u*} and σ_{u*p} (Louis 1981 [dots] and Delage 1997 [stars]) versus Ri_b and b) u_* and u_{*p} (Louis 1981 and Delage 1997) versus Ri_b. Insufficient data does not allow the drawing of a meaningful line beyond $Ri_b = 2.0$ in b). Standard deviation ranges are also shown in b) for some of the data.

Figure 3: Ensemble fluxes versus individual fluxes for sensible heat at the 5 m level on the central 60 m tower from CASES-99. The text correlation values show that the 5 m heat flux for this particular night (as was typical) is correlated less with the average fluxes aloft (0.59) than with fluxes taken at the same 5 m level from towers at 100 m radii (0.71) but greater than from towers at 300 m radii (0.54).

4) Statement of the problem studied

The intent of our investigation, as proposed, is to: 1) understand the dynamics and characteristics of turbulence in the NBL, 2) identify the dominant sources of turbulence, and 3) quantify the heat and momentum fluxes with the intent of devising a revision to existing surface layer theory. We have made significant progress toward each of these goals.

5) Summary of the most important results

We have used CASES-99 nighttime observations to, 1) calculate the sensible heat flux and u_* from two surface layer formulae (Louis 1981, Delage 1997) and compare the parameterized fluxes to those observed, 2) investigate the 'constant flux' assumption and the implications of that for the implementation of surface layer formulae, and 3) characterize the basic statistical behavior of heat and momentum fluxes for statically stable conditions, particularly large dynamic stability. Our results suggest that surface temperature numerical prediction errors, such as cold bias or occasional unrealistic cooling, over flat terrain can be ascribed to the inadequate representation of the impact of non-local NBL phenomena on local fluxes at high Ri_b, the placement of z_1 at high levels compared to the actual surface layer height in the clear sky NBL, and over prediction of cooling fluxes at relatively low Ri_b. We find that the Louis (1981) and Delage (1997) formulas predict zero or near-zero sensible heat fluxes for all $Ri_b > \sim 2.0$ and $Ri_b > 1.0$, respectively, whereas observations show considerable average negative heat flux for all Ri_b. For momentum flux, the Delage formula predicts near zero values for large Ri_b, while the Louis formula predicts more reasonable mean values. As a result cold air would be generated at the ground surface in a numerical model by radiational cooling, but not transferred to the first model grid level above ground, if

model Ri_b became large. Thus, unrealistic vertical temperature gradients could be created which may not be adequately balanced by a radiative parameterization, or otherwise create numerical instability.

We have also investigated the constant flux assumption based on profiles of heat and momentum flux. Using a threshold value of 10% and we find that the average surface layer in the NBL for $Ri_b > 0.2$ is either a few meters deep or undefined. These results suggest that it may be difficult to prescribe a fixed surface layer height in a numerical model, as is currently the practice, and to also expect exclusively similarity-based surface layer formulae to perform adequately at large stability. The near surface heat fluxes were found, in the mean for $Ri_b > 0.2$, to be reasonably constant and non-monotonic with height up to 55 m, making the boundary layer difficult to define, in part because of the influence of increasing intermittency between 20 and 55 m above ground. The u* profile for Rib > 0.2 was consistent with 'upside-down' boundary layer concept (Vickers and Mahrt 2002), making the surface layer undefinable, whereas the mean sensible heat flux profile exhibited a 'mirrored' boundary layer shape.

We also found (Figures 1 and 2) that the Louis (1981) and Delage (1997) formulae overpredicted the magnitude of negative sensible heat flux for $0.1 < Ri_b < 1.0$ and $0.1 < Ri_b < 0.6$, respectively, with this overprediction becoming worse and tending towards higher Ri_b with greater altitude. Momentum flux was also overpredicted by these formulas for most $Ri_b < 0.5$. As a result, at low but positive Ri_b these formulae will transfer cool air at too great a rate to the first model grid point above ground. This behavior can lead to excessive cooling at z_1 if flux divergence is negligible above the surface layer.

CASES-99 observations, and indicated by the scatter, magnitude and standard deviation of H and $u_*$for large Ri_b, (Figures 1 and 2) clearly indicate a wide variety of non-local sources of potential mixing. Our results make it tempting to re-propose (Kondo et al. 1978) that the drag coefficient be a constant or nearly constant value for high Ri_b, allowing continued down-gradient transfer for all variables for $Ri_b > 0$. We propose instead a more physically realistic and comprehensive concept on the basis of the routine occurrence of various external atmospheric phenomena inducing fluxes. This approach introduces to surface layer formulae a random component of a defined probability function that would by physically bounded by far more comprehensive field observations and practically implemented with additional requirements based on model configuration. Further details can be found in Poulos and Burns (2003).

In addition to the above results, in summary we have found (see details in Fritts et al. 2003, Poulos et al. 2002, Blumen et al. 2001, Balsley et al., 2002,)

- CASES-99 data led to characterization of large-scale KH instabilities that appear to play a large, transient role in NBL mixing. This turbulent exchange can frequently, particularly in regions where nocturnal, low-level jets are present, lead to a restructuring of the atmospheric profile, with subsequent influence on inversion strength prediction and surface low temperature prediction.
- CASES-99 data permitted an assessment of ducted structures that appear to be a persistent feature of NBL dynamics. Generally, thought to be gravity waves, these features propagate through the evolving NBL with some significant effects if subjected to shear. In general, these features are responsible of NBL oscillations in pressure, temperature and momentum, as would be expected from gravity wave propagation.
- CASES-99 data led to the discovery of surface flow impacts on NBL wave structure, suggesting a mechanism for wave excitation and contaminant dispersal. In particular, body-forcing has been found to create conditions conducive to vertical wave propagation from an otherwise unknown source: local, small-scale terrain variation with coincident wind direction change. This mechanism would operate over much of the Earth's surface which is characterized by terrain features somewhat similar to the rolling flatlands of southeastern Kansas where CASES-99 was held.

- A catalog of CASES-99 fluxes, intermittency statistics and horizontal correlations has also been produced which will lead to additional publications upon further examination. This archive can be found at http://www.co-ra.com/~shane/ As is clear from the statistics shown therein, the stable NBL fluxes are rather well correlated over many nights, ensembled, but on any given night, poorly correlated even within 100 m radii (e.g. Figure 3).

In summary, the CASES-99 field experiment, which was organized by the co-I's, was an extraordinarily successful investigation of the stable nocturnal boundary layer. Thus, far we have produced and co-edited two Special Issues (Boundary Layer Meteorology and the Journal of Atmospheric Sciences) and generated innumerable publications which describe expanded understanding of the stable and very stable (Ri > 1.0) NBL.

The CASES-99 Special Issue of the Journal of Atmospheric Sciences was presented to the scientific community in honor of our co-I Dr. William Blumen, Professor Emeritus in the Program of Atmospheric and Oceanic Sciences at the University of Colorado at Boulder and initiator of CASES-99, who died on 23 April 2002 at the age of 70. We would like to take a couple paragraphs in this summary to honor Bill's contributions.

Through his involvement with the overarching Cooperative Atmosphere-Surface Exchange Study (CASES), Bill was the progenitor of CASES-99, an investigation of these exchanges under statically stable near surface conditions. He was dedicated to formulating CASES-99 from the ground up, starting with an assessment of interest within the atmospheric science community through announcements at Boundary Layer and other conferences. Scientific goals were crystallized in a concise series of meetings and communications, and Bill either led or directed much of the CASES-99 effort with aplomb.

Some knew Bill most for his achievements in theoretical atmospheric physics, but we recall with fondness his ability to dirty his hands in the months approaching and during the CASES-99 field experiment. We spent many days driving around the countryside of southeastern Kansas with Bill in search of the central site for CASES-99, in search of landowners to obtain permission, in negotiations to see if cattle could be removed from the premises (e.g. the photo above, courtesy Dr. Julie Lundquist), waiting at the offices of the local county seat for the maps required, setting up instrumentation and finally spending many cold, nighttime hours directing aircraft and remote sensing field observation. During those days and nights, in addition to typical banter, we would encourage Bill to discuss his early days in the Navy and at MIT. For the younger researchers, this was like reviewing a portion of the more recent foundations of atmospheric science. As the hours passed so did Bill's wisdom, along with cautionary tales of maintaining standards and honor.

6) Listing of publications

Papers published in peer reviewed journals

Poulos, G. S. and S. P. Burns, 2003:An evaluation of bulk Ri-based surface layer flux formulae for stable and very stable conditions with intermittent turbulence. J. Atmos. Sci. (in press).

Poulos, G. S., 2002: Preface - CASES-99 Special Issue. Bound.-Layer Meteor., 105, 197-198.

M. LeMone, R. L. Grossman, R. L. Coulter, M. L Wesely, G. E. Klazura, G. S. Poulos, W. Blumen, J. K. Lundquist, R. H. Cuenca, S. F. Kelly, E. A. Brandes, S. P. Oncley, R. T. McMillen and B. B. Hicks, 2000: Land-atmosphere interaction research, early results and opportunities in the Walnut River Watershed in southeast Kansas: CASES and ABLE. *Bull. Amer. Meteor. Soc.*, **81**, 757-779.

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Poulos, G. S., 2000: Stable Boundary Layer Heterogeneity. American Geophysical Union - Abstracts, 2000 Fall Meeting, San Francisco, California, December 15-19, 2000

Papers presented at meetings, but not published in conference proceedings

Cohen, E. and G. S. Poulos, 2000: The evolution of two CASES-99 intermittent turbulence events: Fluxes and spectra. *American Meteorological Society - Poster session*, 15th Conference on Boundary Layers and Turbulence, Snowmass, Colorado, 7-11 Aug, 618-621.

Manuscripts submitted, but not published

Poulos, G. S. and LeMone, M. A., 2003: Preface - William Blumen Memorial CASES-99 Special Issue. J. Atmos. Sci. (accepted).

Balsley, B. B, R. Frelich, M. Jones, D. C. Fritts, and S. Vadas, 2003: 3D terrain effects on the stable nocturnal boundary layer, part 1: Observations of gully flows and their impact on vertical motions and wave generation, J. Geophys. Res., to be submitted.

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Technical Reports submitted to ARO

N/A

7) Listing of participating scientific personnel

Dr. Gregory S. Poulos, Colorado Research Associates
Dr. William Blumen, University of Colorado, Boulder
Dr. David C. Fritts, Colorado Research Associates
Dr. Dennis Riggin, Colorado Research Associates
Elisabeth Cohen, Cornell University (summer intern at Colorado Research Associates)
Shane Neuville, University of Colorado, Boulder

8) Report of Inventions

N/A.

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10) Appendixes (Figures 1-3)

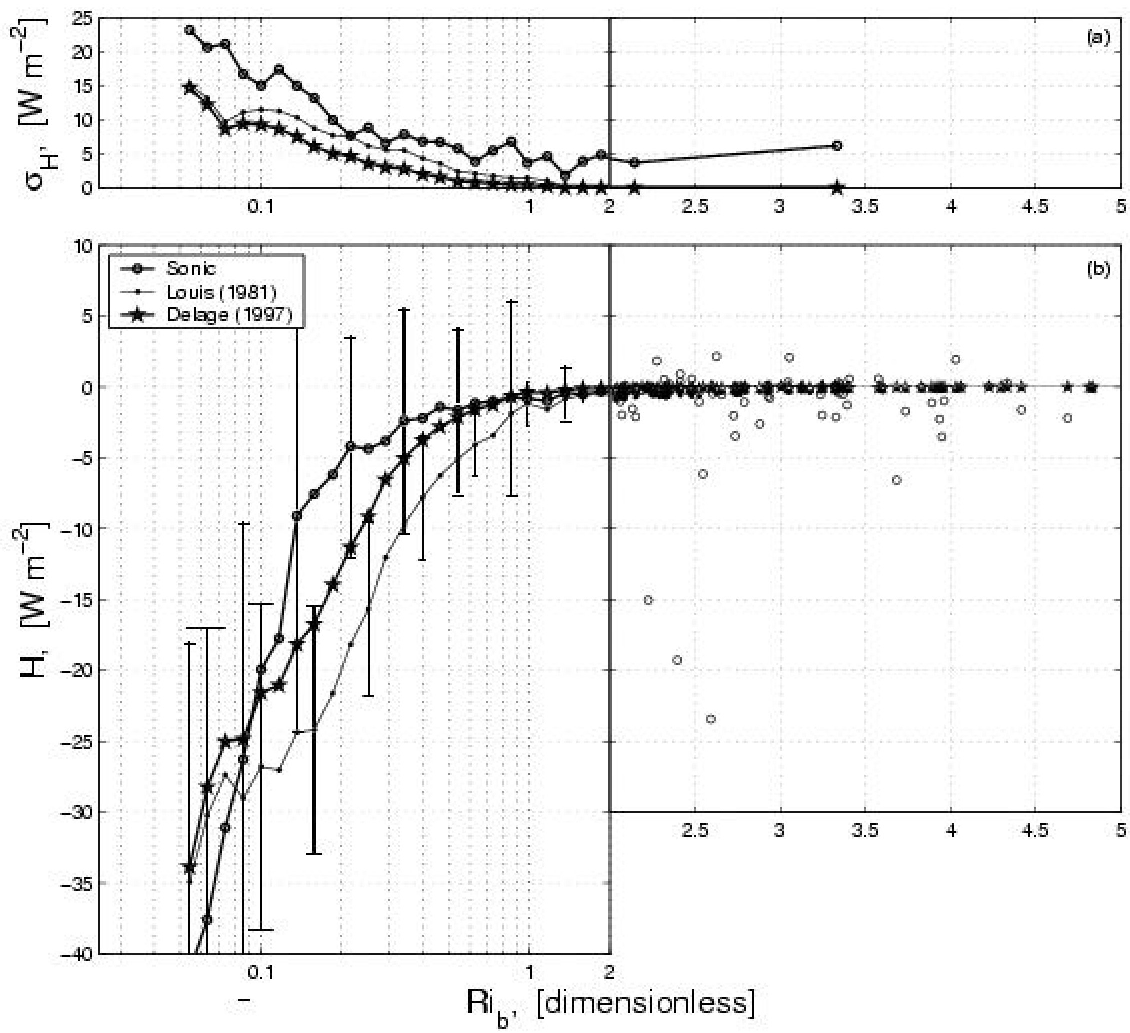

Figure 1: a) σ_H and σ_{Hp} (Louis 1981 [dots] and Delage 1997 [stars]) versus Ri_b and b) H and H_p (Louis 1981 and Delage 1997) versus Ri_b. Insufficient data does not allow the drawing of a meaningful line beyond Ri_b = 2.0 in b). Standard deviation ranges are also shown in b) for some of the data.

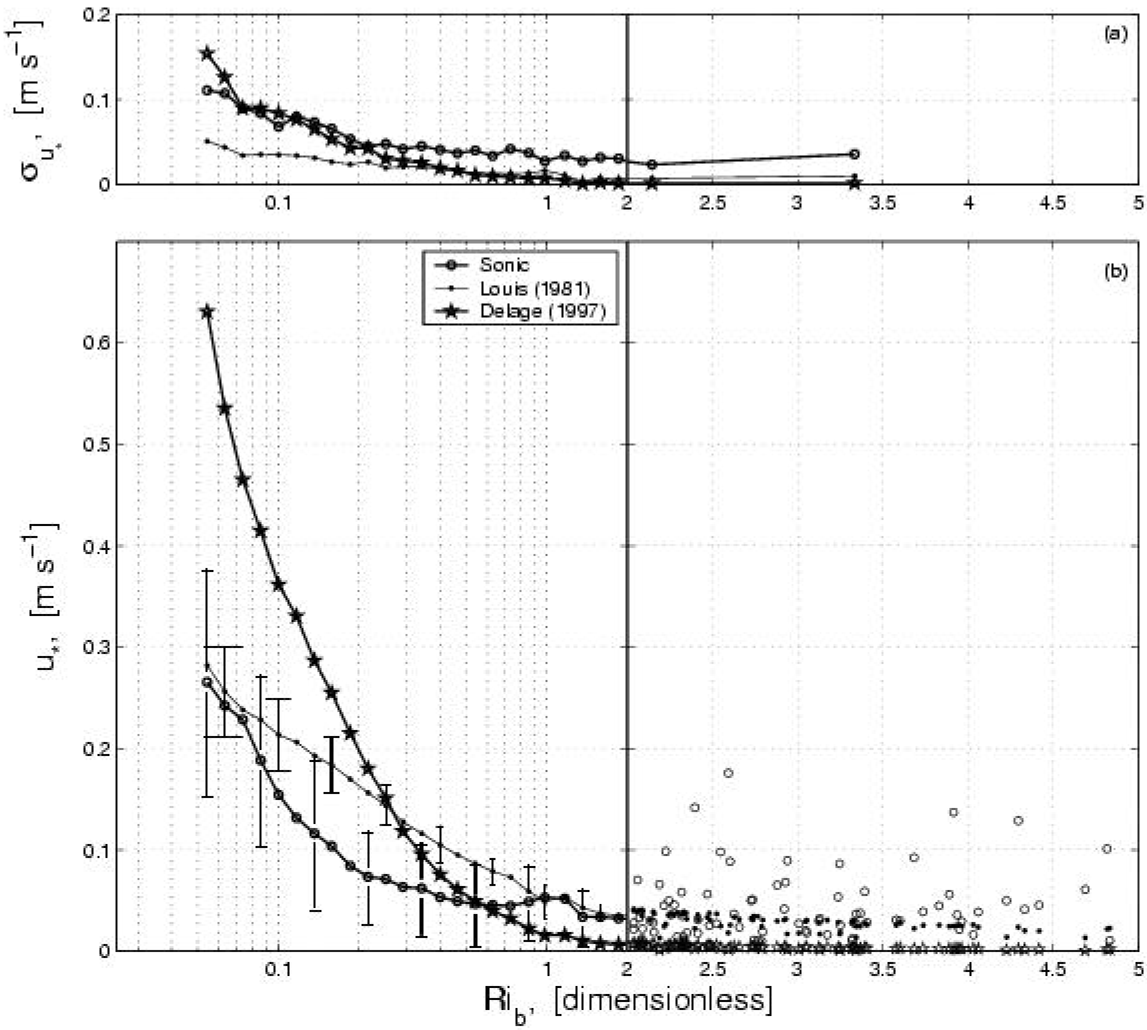

Figure 2: a) σ_{u*} and σ_{u*p} (Louis 1981 [dots] and Delage 1997 [stars]) versus Ri_b and b) u_* and u_{*p} (Louis 1981 and Delage 1997) versus Ri_b. Insufficient data does not allow the drawing of a meaningful line beyond $Ri_b = 2.0$ in b). Standard deviation ranges are also shown in b) for some of the data.

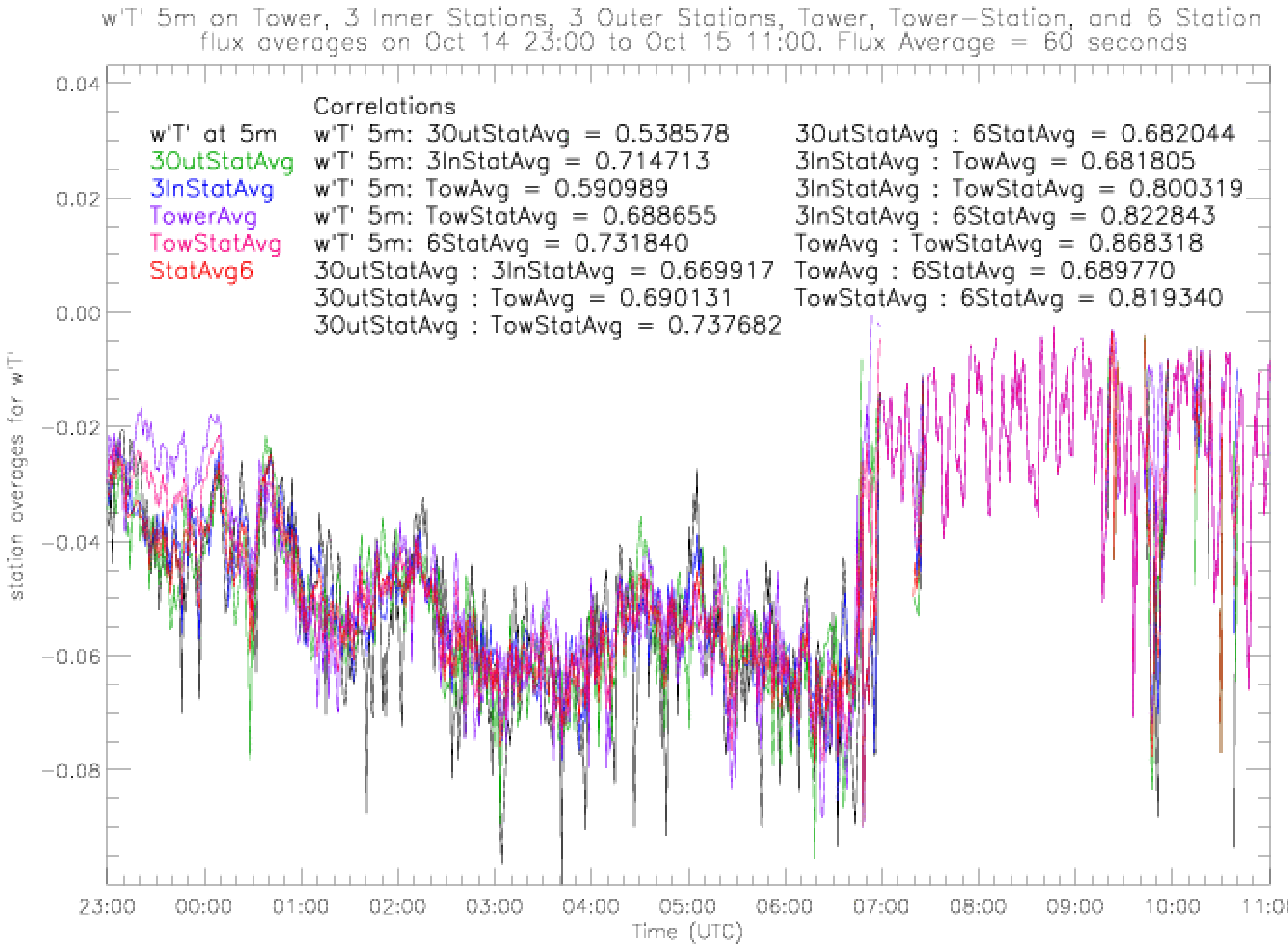

Figure 3: Ensemble fluxes versus individual fluxes for sensible heat at the 5 m level on the central 60 m tower from CASES-99. The text correlation values show that the 5 m heat flux for this particular night (as was typical) is correlated less with the average fluxes aloft (0.59) than with fluxes taken at the same 5 m level from towers at 100 m radii (0.71) but greater than from towers at 300 m radii (0.54).